VSF Measurements and Inversion for RaDyO

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LONG TERM GOALS

Time and space dependent radiance distributions at the sea surface are a function of the shape of the incident distribution on the surface, modification by the sea surface itself from topography and transmission characteristics, and alteration by the Inherent Optical Properties (IOPs) of the surface ocean. Our long term goal is to understand this last controlling factor. With a knowledge of the IOPs, radiance fields can be directly computed from the incident field using the equation of radiative transfer, now embedded in commercially available code.

With the state of current technology and methodologies, the primary obstacles in understanding subsurface IOPs and their high-frequency dynamics are a lack of 1) volume scattering instrumentation, 2) comprehensive inversion models linking the IOPs with the ambient particle fields including bubbles (models which in many cases will require input dependent on 1), and 3) suitably stable, non-intrusive platforms to sample the subsurface ocean. The first two challenges are addressed in this project.

OBJECTIVES

Through RaDyO support we have developed, tested, and deployed a new 17 angle volume scattering function device called the MASCOT. Over 3 million VSFs have now been collected throughout the world's oceans. We have also developed a basis vector least-squares minimization inversion model to retrieve size distributions with associated bulk refractive index of particle subcomponents, including bubbles, minerals, organic water-filled particles, and coated particles. Our objective in ongoing work is to use our extensive data set of polarized and unpolarized angular scattering functions to develop a better understanding of the composition and dynamics of particle fields and how they may in turn affect optical and acoustical energy propagation in near-surface waters, including the surf zone.

APPROACH

MASCOT (Multi-Angle SCattering Optical Tool) has a 30 mW 658 nm laser diode source expanded with a Gallilean 2X beam expander to an approximately 3 mm X 8 mm elliptical shape. A wedge depolarizer is used to provide the unpolarized light needed for VSF determinations. Seventeen independent silicon diode detectors spaced in a semicircle 10 cm around the sample volume measure volume scattering from 10° to 170° at 10° intervals. The total pathlength for all scattering measurements is 20 cm. Independent detectors allow resolution of the VSF without any moving parts and time-consuming scanning. Additionally, each detector can be optimized for its specific dynamic range. Detector field-of-views (FOVs) range from 0.8° to 5° for the different detectors, with the narrowest FOVs associated with the detectors measuring scattering in the forward direction. Using proprietary electronics, a 20 Hz sampling rate for all channels has been achieved while maintaining a worst case signal:noise of 300:1. Relatively fast sampling rates are important in resolving VSFs in the highly dynamic subsurface.

Polarized VSFs were successfully collected with the addition of a filter mount placed in front of the source beam. A linear polarizer was used to obtain scattering from a vertically and horizontally polarized source (in terms of the Mueller scattering matrix elements, (S11+S12)/2 and (S11-S12)/2 are measured, so that S11 and S12 may be derived). Adding polarized scattering increases the amount of information on particle characteristics we are collecting, and is expected to improve our ability to discriminate different particle types (both the number of subpopulations and the accuracy of individual determinations). The degree of linear polarization (S12/S11) is most dependent on the degree of sphericity, particle size, and refractive index.

For VSF inversion modeling, we (Twardowski et al. 2012) have extended the capabilities of existing models (Twardowski et al. 2001; Twardowski and Zaneveld, 2004; Zhang et al. 2005, 2011) by incorporating input from new VSF measurements and by adding bubble particle populations (clean and coated) in the models. Candidate phase functions for particle subpopulations are fit to measured VSFs using a least-squares minimization matrix inversion procedure. These phase functions can be obtained theoretically using Mie theory, DDA, or IGOM techniques, or experimentally in controlled conditions. George Kattawar's group has recently provided DDA-IGOM phase function determinations for asymmetric polyhedrons we are using in inversions. Current work aims to extend the inversions to measurements of linearly polarized scattering.

Deployments for RaDyO have taken place in collaboration with other RaDyO investigators off Scripps Pier, in Santa Barbara Channel, and off Hawaii. For these RaDyO deployments, we have also intermittently integrated a bubble acoustic resonator developed by Svein Vagle, David Farmer, and Helen Czerski. For the Scripps Pier experiment, measurements were made throughout the surfzone. For subsequent field work in SBC and Hawaii, the sensor package was deployed off the R/V Kilo Moana.

WORK COMPLETED

In the past year under partial or complete support from this contract, 16 papers were submitted for peer-review publication, 14 which are currently in print. These papers are the last 16 papers in the PUBLICATIONS section and are highlighted in **bold**.

Recent work continues the assessment of relationships between measurements of polarized volume scattering functions and particle fields for the RaDyO data and other data sets. Two papers are in preparation for this work with two presentations of these results at the Ocean Optics Conference, October 2012. Analysis also continues on evaluating the role of surfactants in stabilizing bubble populations and the cross-validation of 3 different techniques for quantifying bubble size distributions: VSF inversion, acoustic resonator inversion, and in-situ holography. A paper is in preparation, led by

Helen Czerski (U Southampton). Collaborator Sid Talapatra (Johns Hopkins U) also presented some of these results at the SPIE Ocean Sensors and Monitoring Conference in Baltimore in April 2012.

RESULTS

In situ measurement of the degree of linear polarization (DOLP, equivalent to S12/S11 from the Mueller matrix for a randomly oriented particle field) from 10 to 170 degrees has now been completed in approximately 12 disparate oceanic sites around the world. Sample DOLP data from a profile collected in Santa Barbara Channel are provided in **Fig. 1**. Despite the widespread use of polarized laser sources across a diversity of Navy applications, this comprises the first comprehensive data set ever assembled for studying scattering by linear polarized light in the world's oceans. We have also computed DOLP for polydisperse populations of homogeneous spherical particles computed using Lorenz-Mie theory and for nonspherical asymmetric polyhedra particles (mineral-mimicking) with phase functions computed from DDA and IGOM (sample results shown in **Figs. 2-4**). Comparison of the *in situ* data and theoretical results show that Lorenz-Mie theory is inadequate for describing the linear polarization characteristics of oceanic particles, except for bubbles and spherical droplets from emulsions such as oil dispersed in seawater. Scattering functions from asymmetric polyhedra, however, can in many cases effectively reproduce variability in the DOLP observed experimentally. General observations for oceanic polydispersions include: 1) increasing nonsphericity lowers DOLP and shifts the DOLP peak to larger angles; 2) increasing refractive index lowers DOLP, particularly for populations with relatively flat size distributions; and 3) as size distributions become increasingly flat, the DOLP decreases and the maximum shifts to larger angles.

Because nominally spherical particles exhibit strong specificity in VSF shape, with a mid-angle enhancement around 60 to 80 degrees, bubbles and emulsified fluids may be resolved within complex oceanic particle mixtures at volume concentrations at the part per billion level, equivalent to only several 10 μm bubbles or droplets per mL. The DOLP of bubble populations is also unique among all other particle types, as there is effectively no polarization of the scattered beam between 0 deg and the critical angle around 80 deg. This is due to total internal reflection of scattered light off the bubble surface within the water medium, which is not a polarization-specific phenomenon. Optical scattering is currently the only method capable of resolving bubbles and emulsified oil particles less than about 20 μm (where the highest concentrations are observed). A sample plot of a transition from background particle DOLP to a bubble dominated DOLP is provided in **Fig. 5**.

With the Czerski-Vagle-Farmer RaDyO team, we have collected a rich data set of concurrent optical-acoustical measurements that are being used to resolve and validate bubble size distributions down to micron sizes. Results suggest an inflection in bubble size distributions in the 20-40 μm range, which may be the region of delineation between persistent, surfactant stabilized small bubbles and more ephemeral large bubbles subject to rapid buoyant uplift. In data collected in the propeller wash from a passing 40 ft boat with outboard motor, bubbles as large as 50 μm were observed for over 1 hour (**Fig. 6**). Bubbles in this data set were not only resolved with optical scattering and acoustics but with in-situ holography, which additionally resolved turbulence dissipation using particle interference velocimetry.

We have recently also assessed the potential effects of particle orientation on the VSF including its polarization elements in natural waters. In virtually all measurements and models we are aware of, the VSF is assumed to have no dependency on the direction of illumination or the azimuthal plane of scattered radiance. For this assumption to be true, all particles suspended in the water column must be randomly oriented. From simple physics of hydrodynamic flows for the nonspherical particles that comprise virtually all the particles in the ocean, this is not a reasonable assumption. Furthermore, direct evidence from the field, both in volume scattering data (S13/S11 analyses) and holographic imaging, is confirming ubiquitous preferential particle alignment in coastal waters, particularly within density gradients (Talapatra et al., in press). Consequently, it appears that our understanding of the geometry-dependent VSF, and thus transmission through coastal waters, may be significantly biased.

IMPACT/APPLICATIONS

Progress and results represent important steps toward the development and vetting of a multi-angle, in-water VSF device. Knowledge of the Inherent Optical Properties including the VSF can be used to predict and optimize the performance of a host of Naval operations that rely on divers, cameras, laser imaging systems, and active and passive remote sensing systems. These include mine countermeasures, harbor security operations, debris field mapping, anti-submarine warfare, and search and salvage operations. Particles found in the near-surface such as bubbles also impact acoustical transmission. It should be noted that our results represent the first comprehensive data set ever recorded for the VSF in the oceans, and the first measurements of polarized scattering elements *in situ* for undisturbed particle fields.

TRANSITIONS

We expect that our efforts in developing an in-water VSF device and associated inversion techniques to better understand particle dynamics in natural waters will lead to transition as better predictive operational tools for the fleet and the oceanographic research community in the future.

RELATED PROJECTS

This effort is related to ongoing efforts by the PI to develop optical sensors and associated inversion techniques to improve our understanding of the oceanic environment. Current ongoing related projects include:

- developing and testing a sensor system for rapid but high quality assessment of environmental optical conditions to complement, guide, and predict performance of shallow water EO remote sensing for mine countermeasures (ONR LGO, Twardowski)
- investigating the underlying controls of biological camouflage responses in dynamic underwater optical environments (MURI collaboration, Twardowski; URI PIs J. Sullivan and B. Seibel; project lead PI M. Cummings);
- developing improved remote sensing water quality algorithms for coastal waters (NASA, Twardowski; project lead PI Z-P. Lee);
- developing a microscopic holographic camera to image undisturbed, optically relevant particles (NOPP, project lead PI J. Sullivan); and
- developing a surfzone drifter measuring optical attenuation and scattering (ONR SBIR, Twardowski).

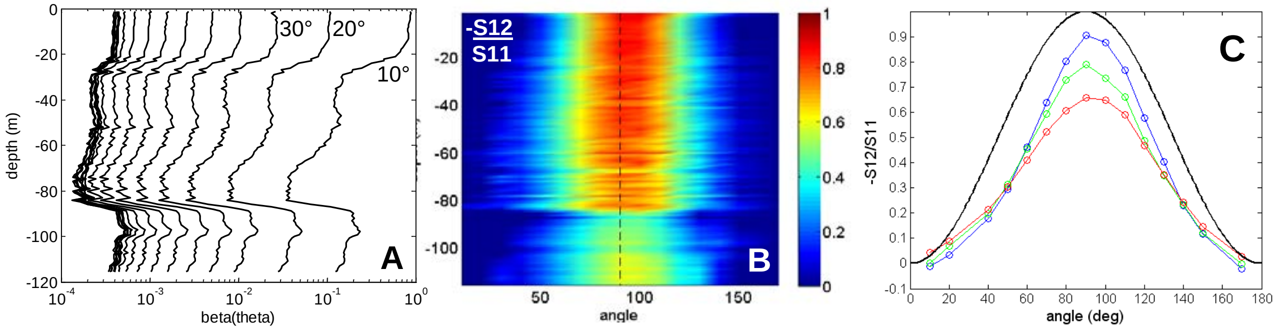

Figure 1. (A) Vertical profile of the VSF resolved from 10 to 170° in 10° increments collected in Santa Barbara Channel. (B) The linear degree of polarization (-S12/S11) as a function of depth and angle, showing a maximum around 0.9 at the very surface, with a steady decrease with depth. The deep scattering maximum exhibited much lower polarization, as low as 0.6 around 90 m. (C) Overlays of –S12/S11 plotted for 3 depths regions, labeled in B. This is the first time these measurements have been made in-situ.

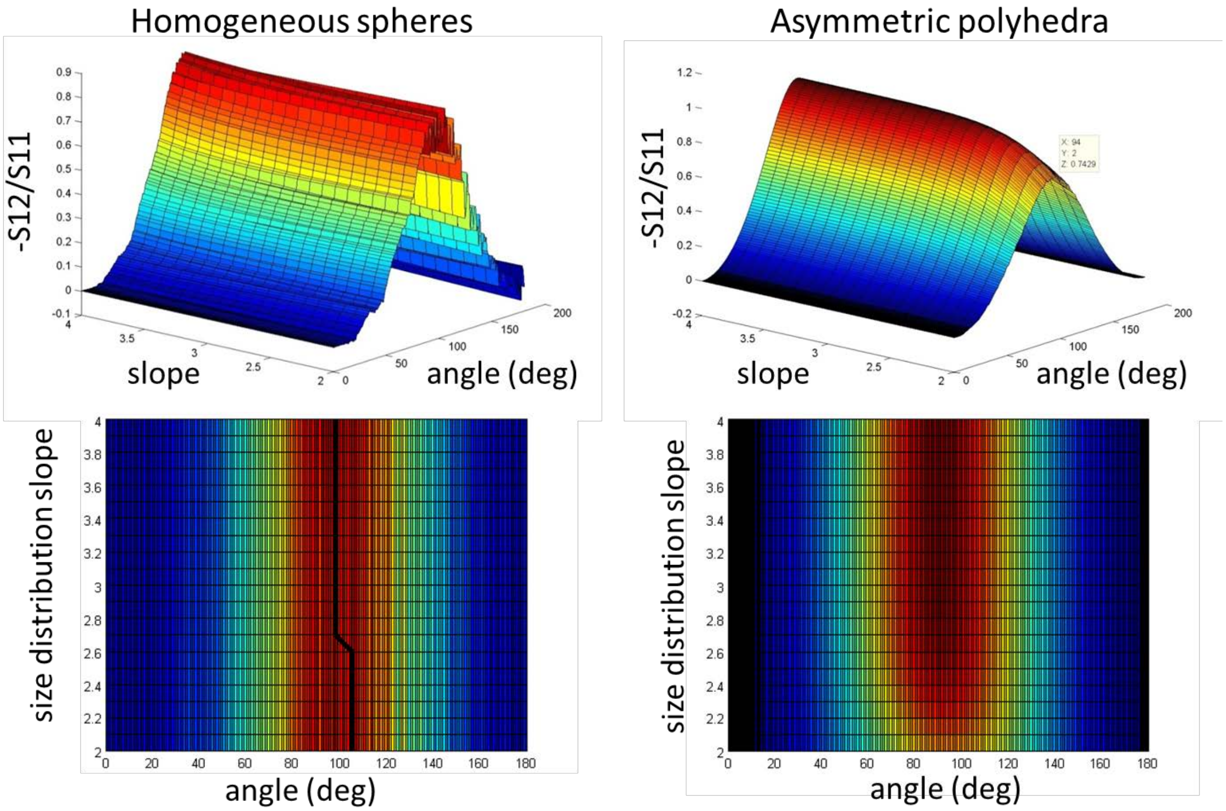

Figure 2. Degree of linear polarization (-S12/S11 from the Mueller scattering matrix) computed for polydispersions of homogeneous spheres (left column) and asymmetric polyhedra (nonspherical, mineral-mimicking particles; right column). The 2D pseudo-color plots are the same data as plotted above. Polydispersion size distributions follow a power law (i.e., Junge-type distribution), with slope varying between 2-4. The black line in the lower left plot corresponds with the angle at which DOLP is at a maximum. Imaginary part of the refractive index was set at 0.002, with the real part, np = 1.02.

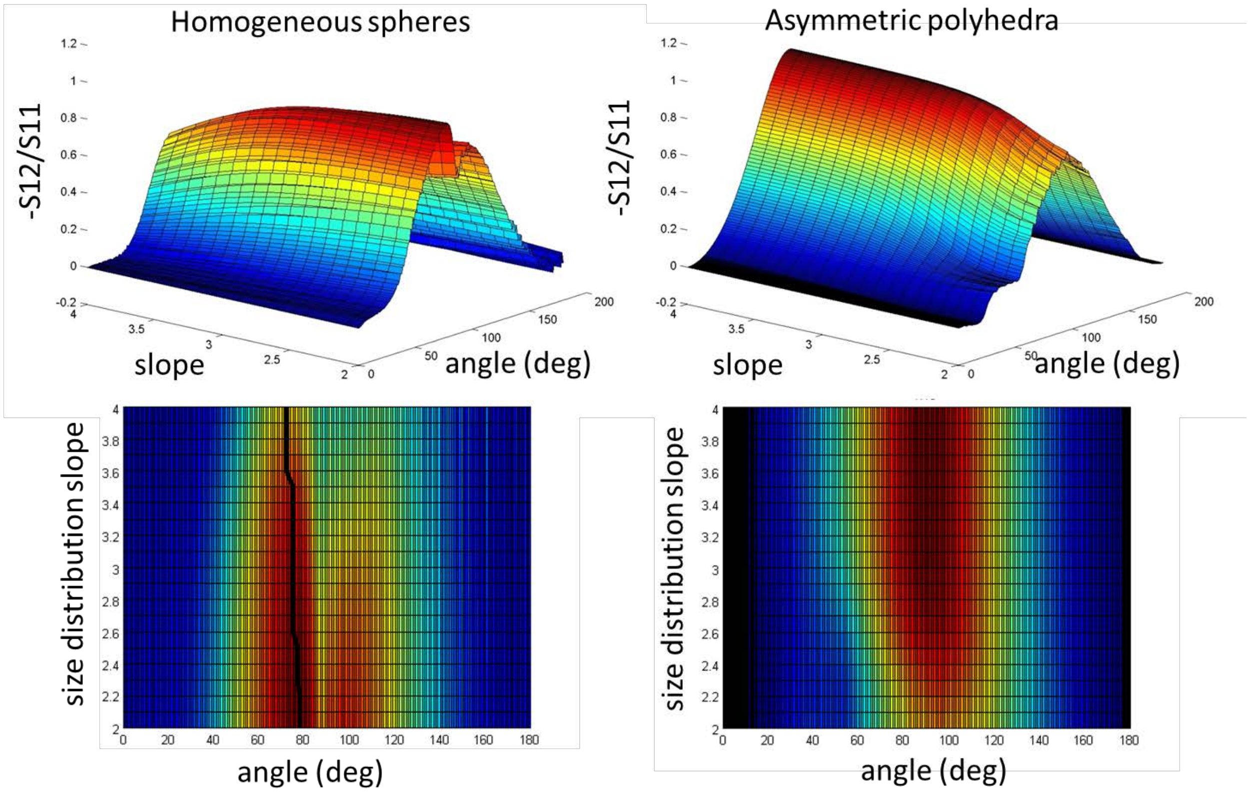

Figure 3. Same as in Fig. 2, with real refractive index, np = 1.10.

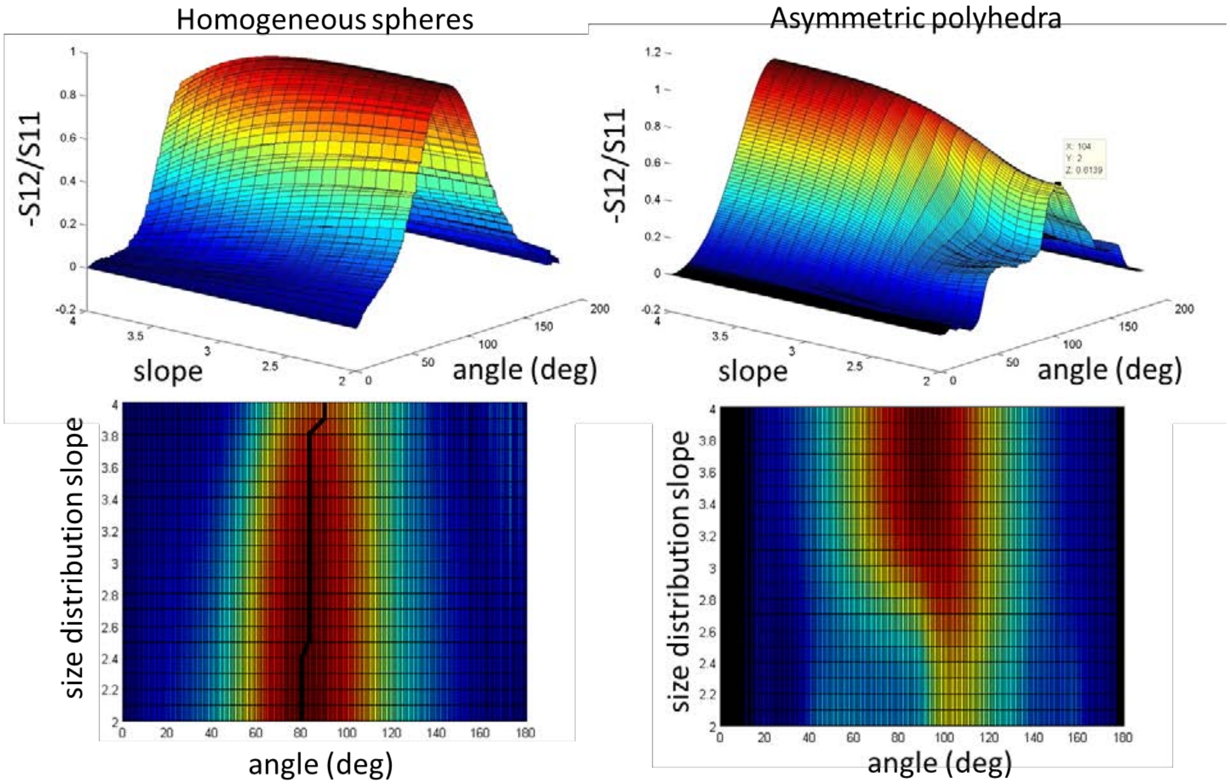

Figure 4. Same as in Fig. 2, with real refractive index, np = 1.20.

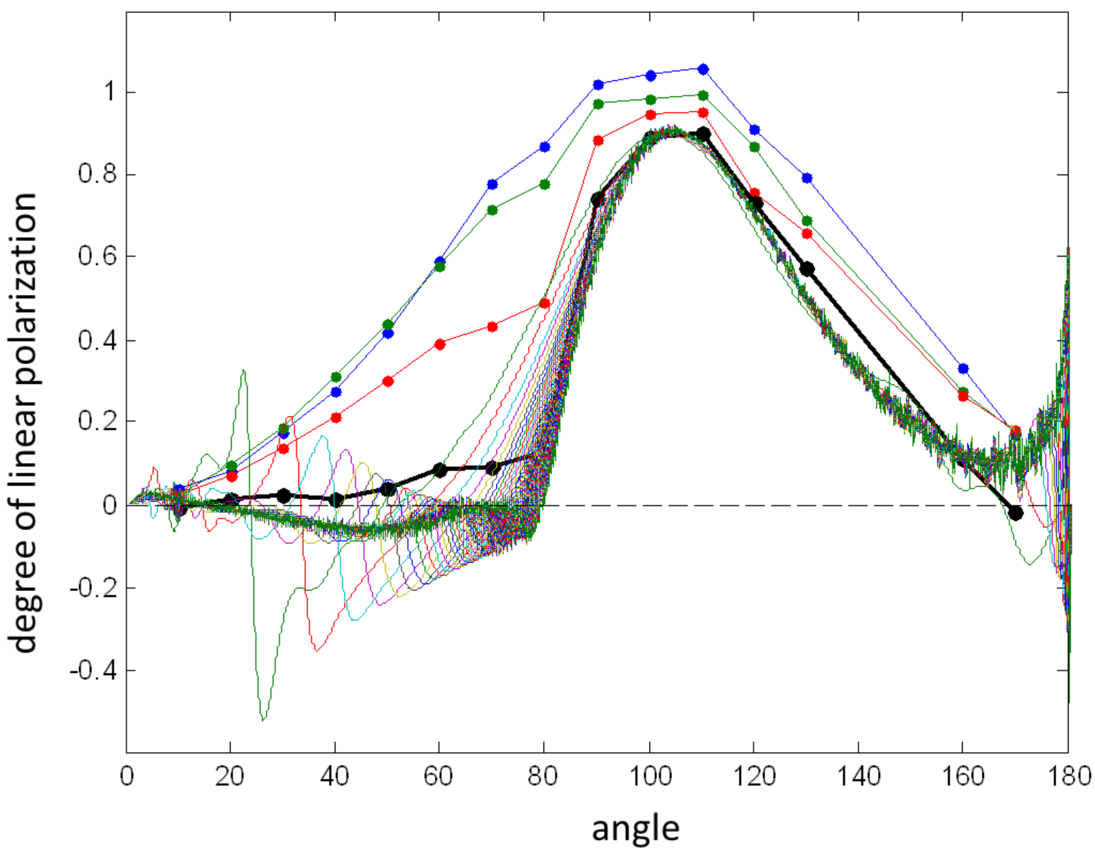

Figure 5. Degree of linear polarization (-S12/S11 from the Mueller scattering matrix) measured in the NY bight under breaking wave conditions (blue, red, green, and black traces), along with DOLP computed from Mie theory for various lognormally distributed populations of bubbles with relative refractive index of 0.75. A transition is observed between the background with little influence from bubbles (blue trace) to a particle population dominated by bubbles that matches Mie theory computations exceedingly well (black trace). In complex oceanic particle populations, the DOLP for bubbles is completely unique.

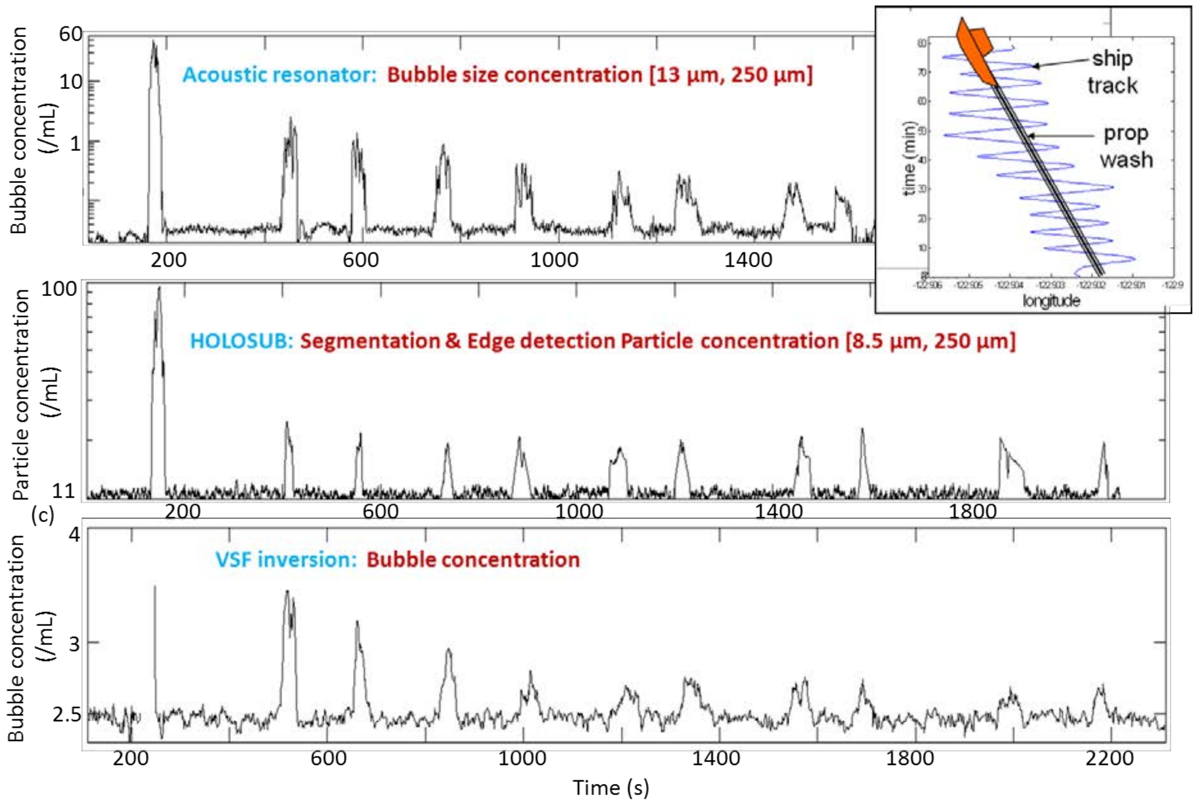

Figure 6. Bubbles resolved in a boat's propeller wash with an acoustic resonator (Czerski, Vagle), a holographic imaging system (Talapatra, Katz, Twardowski, Sullivan), and inversion of the volume scattering function. Inset in the upper right shows the ship tract over time. Bubbles persisted for over 1 hour in surface waters after the boat passed, indicating stabilization by organic surfactants.

PUBLICATIONS

Twardowski, M.S., J.M. Sullivan, P.L. Donaghay, and J.R.V. Zaneveld. 1999. Microscale quantification of the absorption by dissolved and particulate material in coastal waters with an ac-9. *J. Atmos. Ocean. Technol.* **16(12)**:691-707. [refereed]

Boss, E., and M.S. **Twardowski**. 2000. On the relationship of the particulate beam attenuation spectrum and size distribution of oceanic particles. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Coleman, J.E., R.A. Reynolds, M.C. Talbot, M.S. **Twardowski**, M.J. Perry. 2000. Utilization of solar-induced chlorophyll a fluorescence as an indicator of phytoplankton biomass in coastal waters. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2000. In situ spectral absorption (ac-9) measurements as an index of photoprotective/photosynthetic carotenoid ratios. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Moore, C., M.S. **Twardowski**, and J.R.V. Zaneveld. 2000. The ECO VSF - A multi-angle scattering sensor for determination of the volume scattering function in the backward direction. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2000. A model for retrieving oceanic particle composition and size distribution from measurements of the backscattering ratio and spectral attenuation. *Proceedings from Ocean Optics XV*, October 16-20, Monaco.

Twardowski, M.S. 2000. Ocean research in the ocean state. *The Rhode Island State Trooper*, 12(1):107-109.

Boss, E., W.S. Pegau, W.D. Gardner, J.R.V. Zaneveld, A.H. Barnard, M.S. **Twardowski**, G.C. Chang, and T.D. Dickey. 2001. Spectral particulate attenuation in the bottom boundary layer of a continental shelf. *J. Geophys. Res.*, 106(C5):9509-9516. [refereed]

Boss, E., M.S. **Twardowski**, and S. Herring. 2001. Shape of the particulate beam attenuation spectrum and its inversion to obtain the shape of the particulate size distribution. *Appl. Opt.,* 40:4885-4893. [refereed]

Dekshenieks, M.M., P.L. Donaghay, J.M. Sullivan, J.E.B. Rines, T.R. Osborn, and M.S. **Twardowski**. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. *Mar. Ecol. Prog. Ser.,* **223**:61-71. [refereed]

Twardowski, M.S. and A. Barnard. 2001. Observing the ocean: sensing technology and observation platforms. *Maritimes*, 43(4).

Twardowski, M.S., and P.L. Donaghay. 2001. Separating in situ and terrigenous sources of absorption by dissolved material in coastal waters. *J. Geophys. Res.*, 106(C2):2545-2560. [refereed]

Twardowski, M.S., E. Boss, J.B. Macdonald, W.S. Pegau, A.H. Barnard, and J.R.V. Zaneveld. 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in Case I and Case II waters. *J. Geophys. Res.*, 106(C7):14,129-14,142. [refereed]

Gould, R., R. Stavn, M. **Twardowski**, and G. Lamella. 2002. Partitioning optical properties into organic and inorganic components from ocean color imagery. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Rines, J.E.B., P.L. Donaghay, M. Dekshenieks, J.M. Sullivan, and M.S. **Twardowski**. 2002. Thin layers and camouflage: hidden *Pseudo-nitzschia spp*. (Bacillariophyceae) populations in a fjord in the San Juan Islands, Washington, U.S.A. *Mar. Ecol. Prog. Ser.*, 225:123-137. [refereed]

Sullivan, J.M., M.S. **Twardowski**, P.L. Donaghay, and S. Freeman. 2002. Particulate bulk refractive index distributions in coastal regions as determined from backscattering ratio measurements. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Twardowski, M.S., and P.L. Donaghay. 2002. Photobleaching of aquatic dissolved materials: absorption removal, spectral alteration, and their interrelationship. *J. Geophys. Res*, 107(C8). [refereed]

Twardowski, M.S., J.R.V. Zaneveld, and C. Moore. 2002. A novel technique for determining beam attenuation compatible with a small sensor form factor and compact deployment platforms. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Zaneveld, J.R.V., M.S**. Twardowski**, K.S. Shifrin, W.S. Pegau, E. Boss, and I. Zolotov. 2002. Inversion of light scattering measurements to obtain biogeochemical parameters. *Proceedings from Ocean Optics XVI*, November 18-22, Santa Fe, NM.

Dekshenieks, M.M., AL Alldredge, A Barnard, E Boss, J Case, TJ Cowles, PL Donaghay, LB Eisner, DJ Gifford, CF Greenlaw, C Herren, DV Holliday, D Johnson, S MacIntyre, D McGehee, TR Osborn, MJ Perry, R Pieper, JEB Rines, DC Smith, JM Sullivan, MK Talbot, MS **Twardowski**, A Weidemann and JR Zaneveld. 2003. Characteristics, Distribution and Persistence of Thin Layers Over a 48 Hour Period. *Mar. Ecol. Prog. Ser.,* 261:1-19. [refereed]

Eisner, L., M.S. **Twardowski**, and T.J. Cowles. 2003. Relationship between phytoplankton pigment composition and in situ spectral absorption measurements in East Sound, Orcas, Island, WA. *Limnol. Oceanogr.*, 48:632-646. [refereed]

Miller, R., M.S. **Twardowski**, C. Moore, and C. Casagrande. 2003. The Dolphin: Technology to Support Remote Sensing Bio-optical Algorithm Development and Applications. *Backscatter* 14(2):8-12. [refereed]

Boss, E., W. S. Pegau, M. Lee, M. S**. Twardowski**, E. Shybanov, G. Korotaev, and F. Baratange. 2004. The particulate backscattering ratio at LEO 15 and its use to study particles composition and distribution. *J. Geophys. Res.*, 109, C01014, doi:10.1029/2002JC001514. [refereed]

Moore, C., J. Da Cuhna, B. Rhoades, M.S. Twardowski, J.R.V. Zaneveld, J. Dombroski. 2004. A new in-situ measurement and analysis system for excitation-emission fluorescence in natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Schofield, O., J. Kohut, J. Kerfoot, L. Creed, C. Mugdal, S. Glenn, M. **Twardowski**, C. Jones, and D. Webb. 2004. Dawn in the age of ocean robots: what can they see? *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, B. Rhoades, and R. Miller. 2004. The hyperspectral temperature and salinity dependent absorption coefficients of pure water. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., and J.R.V. Zaneveld. 2004. Progress toward a Generalized Optical-Biogeochemical Inversion (GOBI) for natural waters. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Twardowski, M.S., E. Boss, J.M. Sullivan, and P.L. Donaghay. 2004. Modeling spectral absorption by chromophoric dissolved organic matter (CDOM**).** *Mar. Chem.*, 89: 69-88, doi:10.1016/j.marchem.2004.02.008. [refereed]

Zaneveld, J.R.V., C. Moore, A.H. Barnard, M.S. **Twardowski**, and G.C. Chang. 2004. Correction and analysis of spectral absorption data taken with the WET Labs AC-S. *Proceedings of Ocean Optics XVII*, October 25-29, Freemantle, Australia.

Sullivan, J.M., M.S. **Twardowski**, Donaghay, P.L., and Freeman, S.A. 2005. Using Scattering Characteristics to Discriminate Particle Types in US Coastal Waters, *Appl. Opt*., 44:1667-1680. [refereed]

Trees, C.C., P.W. Bissett, H,. Dierssen, D.D.R. Kohler, M.A. Moline, J.L. Mueller, R.E. Pieper, M.S. **Twardowski**, and J.R.V. Zaneveld. 2005. Monitoring water transparency and diver visibility in ports and harbors using aircraft hyperspectral remote sensing. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Twardowski, M.S., M. Lewis, A. Barnard, J.R.V. Zaneveld. 2005. In-water instrumentation and platforms for ocean color remote sensing applications. *In:* Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 69-100. [refereed]

Twardowski, M.S., J.R.V. Zaneveld, C.M. Moore, J. Mueller, C. Trees, O. Schofield, S. Freeman, T. Helble, and G. Hong. 2005. Diver visibility measured with a compact scattering-attenuation meter (SAM) compatible with AUVs and other small deployment platforms. *Prodeedings from SPIE Port and Harbor Security Conference*, Vol. 5780, February, Orlando, FL.

Zaneveld, J.R.V., M.S. **Twardowski**, M. Lewis, and A. Barnard. 2005. Radiative transfer and remote sensing. *In*: Remote Sensing of Coastal Aquatic Waters, R. Miller and C. Del-Castillo [Eds.], Springer-Kluwer Publishing, pp. 1-20. [refereed]

Aurin, D., H. Dierssen, and M. **Twardowski**. 2006. Absorption, Backscatter and Chlorophyll Algorithms for Ocean Color Remote Sensing in Long Island Sound. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

Sullivan, J.M., M.S. **Twardowski**, J.R.V. Zaneveld, C. Moore, A. Barnard, P. Donaghay, and B. Rhoades. 2006. The hyperspectral temperature and salinity dependencies of absorption by water and heavy water in the 400-750 nm spectral range. *Appl. Opt.*, 45:5294-5309. [refereed]

Twardowski M., and M. Jonasz. 2006. VSF at the small angles for natural dispersions and power-law slopes (www.tpdsci.com/Tpc/VsfSmlAngNatDspSlp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Derivation (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Twardowski M., and M. Jonasz. 2006. Power law in spectral scattering by natural dispersions: Finite range of the particle diameter (www.tpdsci.com/Tpc/AtnCfSptPwLwNatDsp.php). In: *Topics in Particles and Dispersion Science* (www.tpdsci.com). [refereed]

Zaneveld, J.R.V, M.S. **Twardowski**, and C. Moore. 2006. Total scattering coefficient meter. *Proceedings of Ocean Optics XVIII*, October 9-13, Montreal, Canada.

Huot, Y., M. Babin, F. Bruyant, C. Grob, M. S. **Twardowski**, and H. Claustre. 2007. Does chlorophyll *a* provide the best index of phytoplankton biomass for primary productivity studies? *Biogeosciences*, 4:853-868, www.biogeosciences.net/4/853/2007/. [refereed]

Huot, Y., A. Morel, M. **Twardowski**, D. Stramski, and R. Reynolds. 2007. Particle optical backscattering along a chlorophyll gradient in the upper layer of the eastern South Pacific. *Biogeosciences*, http://www.biogeosciences-discuss.net/4/4571/2007/bgd-4-4571-2007.pdf. [refereed]

Twardowski, M.S., H. Claustre, S.A. Freeman, D. Stramski, and Y. Huot. 2007. Optical backscattering properties of the “clearest” natural waters. *Biogeosciences*, 4, 1041–1058, www.biogeosciences.net/4/1041/2007/. [refereed]

Bell, J., M. **Twardowski**, C. Moore, and A. Barnard. 2008. Comprehensive optical merge processing and acquisition software system (COMPASS) for comprehensive user correction of WET Labs absorption and attenuation data. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Glenn, S., C. Jones, M. **Twardowski**, L. Bowers, J. Kerfoot, J. Kohut, D. Webb, and O. Schofield. 2008. Glider observations of sediment resuspension in a Middle Atlantic Bight fall transition storm. *Limnol. Oceanogr.*, 53(5, part II), 2180-2196.

Moore, C., J. Koegler, W. Strubhar, M. **Twardowski**, A. Barnard, A. Derr, and R. Zaneveld. 2008. The next generation beam attenuation meter (BAM) for autonomous underwater vehicles. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Nencioli, F., G. Chang-Spada, and M. **Twardowski**. 2008. Optical Characterization of an Eddy Induced Diatom Bloom West of the Island of Hawaii. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Sciandre, A., D. Stramski, M. Babin, M. **Twardowski**, and C. Grob. 2008. Diel and spatial variability of particle size distribution in the eastern south Pacific. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Stramski, D., R. Reynolds, M. Babin, H. Claustre, S. Kaczmarek, M. Lewis, R. Rottgers, A. Sciandra, M. Stramska, and M. **Twardowski**. 2008. Relationships between POC and optical properties of surface waters in the South Pacific and Atlantic Oceans. Biogeosciences, 5: 171-183, www.biogeosciences.net/5/171/2008/. [refereed]

Tonizzo, A., J. Zhou, A. Gilerson, T. Iijima, M. **Twardowski**, D. Gray, R. Arnone, B. Gross, F. Moshary, and S. Ahmed .2008. Polarization measurements in coastal waters using hyperspectral multi-angular sensor. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Twardowski, M., S. Freeman, X. Zhang, S. Vagle, and R. Zaneveld. 2008. Resolving surf zone particle dynamics with high sampling rate volume scattering function measurements. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Zhang, X., M. **Twardowski**, C. Hu, and M. Lewis. 2008. Retrieving size and optical properties of individual particle populations from the volume scattering function. *Proceedings of Ocean Optics XIX*, October 6-9, Barga, Italy.

Gordon, H.R., M.R. Lewis, S.D. McLean, M.S. **Twardowski**, S.A. Freeman, K.J. Voss, and G.C. Boynton. 2009. Spectra of particulate backscattering in natural waters. *Optics Express*, 17(18), 16192-16208. [refereed]

Aurin, D., H.M. Dierssen, M.S. **Twardowski**, and C.S. Roesler. 2010. Optical complexity in Long Island Sound and implications for coastal ocean color remote sensing. *Journal of Geophysical Research*, 115, C07011, doi:10.1029/2009JC005837. [refereed]

Chang, G., and M. **Twardowski**. 2010. Point spread functions and visibility: Gaining clarity on image processing in natural waters. Proc. Ocean Optics XX, Anchorage, AK, Sep 27-Oct 1.

Czerski, H., M. **Twardowski**, S. Vagle, and M. Slivkoff. 2010. Resolving bubble size distributions and dynamics in near-surface waters with optics and acoustics. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Nencioli, F., G. Chang, M. **Twardowski**, and T.D. Dickey. 2010. Optical characterization of an eddy-induced diatom bloom west of the island of Hawaii. *Biogeosciences*, 7:151-162. [refereed]

Randolph, K., H. Dierssen, M. **Twardowski**, C. Zappa, A. Cifuentes-Lorenzen, and S. Freeman. 2010. Optical measurements of bubble populations during large scale wave breaking in the southern ocean and their significance to remote sensing reflectance. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Slivkoff, M., W. Klonowski, M. **Twardowski**, and S. Freeman. 2010. Determining the near forward volume scattering function from the LISST-100X particle size analyzer. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Spada, F., G. Chang, M. **Twardowski**, and S. Freeman. 2010. Cost Effective Platforms for the Deployment of Optical Sensors in Dynamic Environments. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Sullivan, M.S. **Twardowski**, J Katz, J Hong, S Talapatra, and P. Donaghay. 2010. Understanding particle dynamics using in-situ holographic microscopy. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 – Oct.

Talapatra, S., A.R. Nayak, C. Zhang, J. Hong, J. Katz, M. **Twardowski**, J. Sullivan, and P. Donaghay. 2010. Characterization of organisms, particles, and bubbles in the water column using a free-drifting, submersible, digital holography system. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Twardowski, M., X. Zhang, S. Freeman, M. Slivkoff, J. Sullivan, H. Czerski, S. Vagle, Y. You, and G. Kattawar. 2010. Inverting the Volume Scattering Function to Infer Particle Composition at the Near-Surface. *Proc. Ocean Optics XX*, Anchorage, AK, Sep 27 - Oct 1.

Voss, K.J., S. McLean, M. Lewis, C. Johnson, S. Flora, M. Feinholz, M. Yarbrough, C. Trees, M. **Twardowski**, D. Clark. 2010. An example crossover experiment for testing new vicarious calibration techniques for satellite ocean color radiometry. *J Atmos Oceanic Tech*, 10.1175/2010JTECHO737.1. [refereed]

Dombroski, J., and M. **Twardowski**. 2011. Identification of fluorophoric components of dissolved organic matter in Narragansett Bay, Rhode Island using excitation-emission matrices and Parallel Factor Analysis (PARAFAC). *Science of the Total Environment*, in review. [refereed]

Lee, Z., V. Lance, S. Shang, R. Vaillancourt, S. Freeman, B. Lubac, B. Hargreaves, C. Del Castillo, R. Miller, M. **Twardowski**, G. Wei. 2011. An assessment of optical properties and primary

production derived from remote sensing in the Southern Ocean (SO GasEx). *J Geophys Res*, 116, C00F03, doi:10.1029/2010JC006747. [refereed]

Sullivan, J., J. Katz, S. Talapatra, M. **Twardowski**, J. Hong, and P. Donaghay. 2011. Using in-situ holographic microscopy for ocean particle characterization. *Proc. SPIE OCEANS11*.

Sullivan, J.M., and M.S. **Twardowski**. 2009. Angular shape of the volume scattering function in the backward direction. Applied Optics, 48:6811-6819.

Tonizzo, A., J. Zhou, A. Gilerson, M. Twardowski, D. Gray, R. Arnone, B. Gross, F. Moshary, and S. Ahmed. 2009. Polarization measurements in coastal waters: hyperspectral and multiangular analysis. Optics Express, 17, 5666-5683.

Zhang, X., L. Hu, M.S. **Twardowski**, and J.M. Sullivan. 2009. Scattering by solutions of major sea salts. Optics Express, 17:19580-19585.

Chang, G., M.S. **Twardowski**, Y. You, M. Moline, P. Zhai, S. Freeman, M. Slivkoff, F. Nencioli, and G. Kattawar. 2010. Effects of optical variability on the prediction of underwater visibility. Applied Optics, 49(15):2784-2796.

Bhandari, P. K. Voss, L. Logan, and M. **Twardowski**. 2011. The variation of the polarized downwelling radiance distribution with depth in the coastal and clear ocean. J Geophys Res, 116, C00H10, doi:10.1029/2011JC007320.

Chang, G. and M. **Twardowski.** 2011. Effects of physical forcing and particle characteristics on underwater imaging performance, J Geophys Res, 116, C00H03, doi:10.1029/2011JC007098.

Czerski, H., M. **Twardowski**, X. Zhang, and S. Vagle. 2011. Resolving size distributions of bubbles with radii less than 30 microns with optical and acoustical methods, J Geophys Res, 116, C00H11, doi:10.1029/2011JC007177.

You, Y., A. Tonizzo, A.A. Gilerson, M.E. Cummings, P. Brady, J.M. Sullivan, M.S. **Twardowski**, H.M. Dierssen, S.A. Ahmed, and G.W. Kattawar. 2011. Measurements and simulations of polarization states of underwater light in clear oceanic waters, Optics Express, 50(24):4873-4893.

Zhang, X., M.S. **Twardowski**, and M. Lewis. 2011. Retrieving composition and sizes of oceanic particle subpopulations from the volume scattering function. Appl. Optics, 50:1240-1259.

Dickey, T. and Others. 2012. Recent Advances in the Study of Optical Variability in the Near-surface and Upper Ocean. J Geophys Res., 117, C00H20, doi:10.1029/2012JC007964.

Gleason, A., K. Voss, H.R. Gordon, M. **Twardowski**, J. Sullivan, C. Trees, A. Weidemann, J-F Berthon, D. Clark, and Z-P Lee. 2012. Detailed validation of the bidirectional effects in various Case I and Case II waters. Optics Express, 20(7), 7630-7645.

Groundwater, H., M.**Twardowski**, H. Dierssen, A. Sciandre, and S. Freeman. 2012. Determining oceanic particle size distributions and particle composition: a new SEM-EDS protocol with validation and comparison to other methods. Journal of Atmospheric and Oceanic Technology, 29, 433:449, DOI: 10.1175/JTECH-D-11-00026.1.

Randolph, K. H. Dierssen, M. **Twardowski**, A. Cifuentes Lorenzen, C. Zappa. 2012. Optical measurements of bubble size distributions at 6-9 m depths generated by large-scale breaking waves in the Southern Ocean. J Geophys Res., in review.

Slivkoff, M., W. Klonowski, M. **Twardowski**, and S. Freeman. 2012. Determining the near forward volume scattering function from the LISST-100X particle size analyzer. Journal of Atmospheric and Oceanic Technology, in review.

Sullivan, J., M. **Twardowski**, J.R.V. Zaneveld, and C. Moore. 2012. Measuring optical backscattering in water, In: A. Kokhanovsky (Ed), Light Scattering Reviews 7: Radiative Transfer and Optical Properties of Atmosphere and Underlying Surface, Springer Praxis Books, DOI 10.1007/978-3-642-21907-8_6, pp. 189-224.

Twardowski, M., X. Zhang, S. Vagle, J. Sullivan, S. Freeman, H. Czerski, Y. You, L. Bi, and G. Kattawar. 2012. The optical volume scattering function in a surf zone inverted to derive sediment and bubble particle subpopulations, J Geophys Res, 117, C00H17, doi:10.1029/2011JC007347.

HONORS/AWARDS/PRIZES

WET Labs Postdoctoral Fellowship, 1998.

Early Career Faculty Award, Office of International Research and Development, Oregon State University, 2000.

ASEE Visiting Faculty Fellowship, Naval Research Labs, Stennis Space Center (R. Arnone, A. Weidemann) and Washington, D.C., (Curt Davis), 2000.

Adjunct Professor, University of Rhode Island, 2003.

Adjunct Professor, University of Connecticut, 2005.

Spinoff technology selection, NASA Innovative Partnership Program, http://www.sti.nasa.gov/tto/Spinoff2005/PDF/accessible.pdf, 2005.

NATO Visiting Researcher Fellowship, Naval Underwater Research Centre, La Spezia, Italy, 2010.